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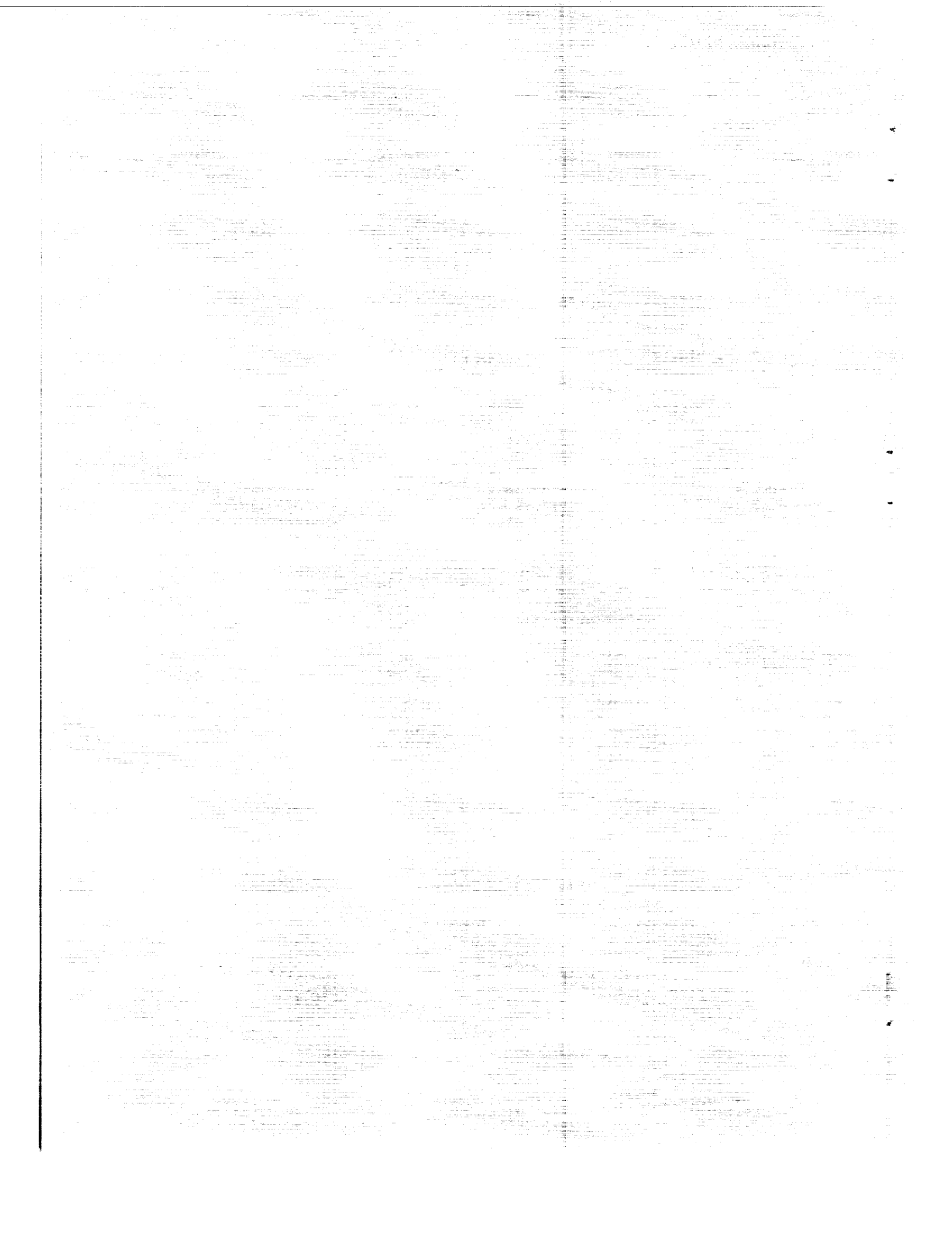

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INTRODUCTION

At the present time in research and industry, the insulating properties of the vacuum are widely used. Particle accelerators, X-ray tubes, cathode-ray tubes, electron microscopes, and vacuum condensers - to name a few - depend for their operation on the electrical strength of vacuum gaps. In connection with this came the need to study and explain the mechanism of the initiation and growth of electrical discharges in high vacuum.

As the pressure of a gas is reduced (usually such that $p < 10^{-3} - 10^{-4}$ mm Hg), the mean free path of the molecules and the charge carriers (electrons and ions) become larger than the distance between the electrodes. Under these conditions the ions and the electrons do not, for all practical purposes, collide with the molecules of the gas remaining in the chamber. Ionization does not occur, and the regeneration processes, which are necessary for the formation of the gas discharge, do not develop. Yet experiments show that such a high vacuum interlayer is still not an ideal insulator. Under certain conditions there will always be a discharge. Just as in gas breakdown at higher pressures, currents can develop across the vacuum gap which are limited only by the external circuit resistance. Most of the experimental data indicate that the breakdown potential, for a given electrode spacing, is independent of further reduction of pressure. Therefore, all of the charge carriers must come either from the electrodes or from the walls of the apparatus.

Vacuum, as any real insulator, possesses a finite conductivity. If we disregard the negligible influence of the residual gases, and also the currents of thermionic emission, which are insignificant at room temperature, then the steady-state conductivity can be considered to be due to field emission. A relation for the current density of field emission can be derived on the basis of quantum mechanical concepts, taking

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into account the forces of electrical nature. If E is the intensity of the electric field at the cathode in volts per centimeter, and φ is the work function in electron volts, then the current density j at the cathode in amperes per square cm is expressed in the following form:

$$j = 1.55 \times 10^{-6} \frac{E^2}{\varphi} e^{-\frac{6.85\times10^{7}\varphi^{3/2}}{E}\psi\left(\frac{3.78\times10^{-4}\sqrt{E}}{\varphi}\right)} \qquad (1)$$

The values of $\psi\left(\frac{3.78 \times 10^{-4}\sqrt{E}}{\varphi}\right)$ can be obtained from special tables or graphs.

Experimental tests confirm the validity of equation (1). Examination of the equation shows that for field intensities less than 10^7 v/cm the field emission currents are very small. As the intensity is increased, the current density increases rapidly. Usually, in actual practice, the currents of field emission become already measurable in fields of the order of 10^6 v/cm and sometimes as low as 10^5 v/cm. However, these field intensities are calculated without taking into account the roughness of the cathode surface. On microscopic irregularities the fields are larger, and emission is determined not by the whole surface of the cathode, but by these irregularities. Therefore, when the current density from a real surface is calculated, the roughness and the area of the emitting surface must be taken into consideration.

Currents of field emission, theoretically calculated and experimentally measured for potentials close to the vacuum gap breakdown, are several orders of magnitude less intense than those which can develop during breakdown. Consequently, other processes must exist which insure the rapid introduction of large quantities of charge carriers into the vacuum gap, and the resulting large currents, during breakdown.

Experimental investigations show that the development of breakdown in high vacuum can be divided into two stages. The first stage is characterized by low pressure, directional movement of ions and electrons, and the presence of X-ray emission at the anode. In the first stage, the basic processes which define the initiation of breakdown take place: the liberation of charge carriers, gas, and metal vapor from the electrodes and the walls of the vacuum container. The first stage is terminated by a rapid increase in current and a decrease in potential across the gap.

The second stage, the maintenance of a vacuum arc, is characterized by an increased pressure between the electrodes, a small gap potential,

and a large current. The duration and physical appearance of the vacuum arc depends essentially on the properties of the external circuitry.

It has been established that the phenomena observable in small vacuum gaps, under relatively small potentials, differ from the phenomena taking place in large gaps with large potentials. The mechanisms of breakdown in uniform electric fields and in very nonuniform fields differ, also. In practical systems, the presence of an adsorbable gas layer on the electrodes, and their dirtiness, has a large influence on the development of breakdown. The vacuum breakdown is greatly altered by the presence near the electrodes of insulators, which are an indispensable part of any electro-vacuum apparatus.

In the last decade there appeared a significant number of works devoted to the study of the mechanism of initiation and development of breakdown in high vacuum. Numerous attempts were made to explain the phenomena observable during the breakdown of different vacuum gaps and with different forms of electrodes. Considerable experimental material has accumulated.

The present work is devoted to the presentation of the most important experimental data and hypotheses which explain the mechanism of the development of high vacuum breakdown. We limited our task to the questions connected with the first stage of breakdown in a simple two-electrode system. In this work we do not consider the vacuum breakdown which is caused by the ignition spark in high vacuum. Also, the phenomena taking place in the second stage of breakdown (burning of the vacuum arc) are not discussed here.

I. ELECTRICAL BREAKDOWN IN HIGH VACUUM

1. Experimental Data

The breakdown potential of the vacuum gap greatly depends on the conditions of the experiment. Since the charge carriers which provide the breakdown currents come from the bounding surfaces of the vacuum chamber, the breakdown potential is determined by the configuration of the electrodes and the walls of the tube, their characteristics, and the condition of their surfaces. The more polished the electrode surface, and the better it is cleaned and degassed, the higher the breakdown potential. The vacuum breakdown takes place at higher potentials if the electric field is nearly uniform.

Breakdown potential depends also on the electrode material. In table I are given the data obtained by Anderson on the influence of the electrode material on the breakdown potential for nearly uniform fields

and a vacuum gap of 1 mm (ref. 1). The breakdown potential of the vacuum gap increases with an increase in the distance between electrodes. However, only for small distances (hundreds of mm) and not very large potentials (up to 20 - 50 kv) can this dependence be considered proportional, for nearly uniform fields. In this case the field intensity at breakdown does not change with the increase of the electrode gap (refs. 2 and 54).

A different relation between potential and gap distance is observed for long distances and large potentials, even for nearly uniform fields. The experimental curves in this case agree satisfactorily with the formula (ref. 3)

$$U = (Cd)^{1/2}$$

where U is the breakdown potential of the vacuum gap, d is the distance between electrodes, and C is Constant. Thus, the field intensity corresponding to the breakdown decreases with increasing gap, and breakdown depends not only on the field strength at the cathode but also on the total potential across the vacuum gap.

For sufficiently large potentials and electrode distances, the simple (no-breakdown) conductivity appears to be of a different nature. Anderson investigated the before-breakdown currents up to potentials of 120 kv in conditions of nearly uniform fields. The magnitude of these currents was of the order of 10^{-7} - 10^{-8} amp. It is established that the pre-breakdown currents in this case are determined not only by the field intensity at the cathode, as for field emission, but also by the potential between electrodes. Anderson assumes that positive ions from the anode take part in conductivity. Ions bombarding the cathode can knock out of it some electrons which support vacuum conductivity. The assumption that metal ions are liberated from the anode under high interelectrode potentials is supported by a test made by Anderson. The anode and cathode were made of two different metals, copper and steel, respectively. The gap between the electrodes was held for several minutes at a potential close to the breakdown potential. After this the material of the anode (copper) was found in a visible quantity on the steel cathode.

In the case of a poorly degassed anode, positive ions appear, due to the liberation of gas from the anode and its ionization. The effects of the production of gaseous ions under the influence of electron bombardment of a non-degassed anode surface, and also bombardment of a glass surface, are investigated in the works of Bennett (refs. 4 and 5).

Numerous experiments by different authors show that the breakdown potential can be considered independent of the remaining gases if the mean free path of the molecules is larger than the dimensions of the

chamber. Experiments were conducted in the pressure region 10^{-3} - 10^{-7} mm Hg. However, the pressure of the remaining gas is closely connected with the degree of degassing of the electrodes - with the quantity of gases adsorbed on the surfaces of the electrodes and the walls of the tube - and the breakdown potential depends greatly on the degree of degassing. It follows that the pressure of the remaining gas has some influence on the breakdown potential (refs. 6, 7, and 8).

Recently, there appeared some indication of an increase in the electrical strength of a vacuum gap with an increase in pressure of the residual gas. According to McKibben and Boyer's data (ref. 9), in an uneven-section linear accelerator with a diameter of 200 mm and a length of approximately 560 mm, the breakdown potential greatly increased when the pressure was increased up to 1×10^{-4} mm Hg. According to Turner (ref. 10), the addition to the residual gas of hydrogen, helium, ozone, and argon in definite proportions limits the phenomena connected with breakdown.

Linder and Christian (ref. 11), while investigating the operation of a high-voltage generator (365 kv), discovered the dependence of the limiting potential of the generator on the pressure of the residual gas. In the region 10^{-6} - 10^{-4} mm Hg the limiting potential of the generator is constant. With further increase in pressure, the potential increases and reaches a maximum at approximately 10^{-3} mm Hg. Further increase in pressure results in a rapid decrease in the limiting potential.

At approximately the same pressures (10^{-3} - 10^{-2} mm Hg for helium, air, and argon) some peculiarities in the development of the discharge, in ignition spark tubes as well as double electrode systems, were discovered by Kustova and Reichrudel (ref. 12). In particular, the integral intensity of radiation in this region of pressures has a maximum. The authors connect this maximum with an increase in time of formation of the discharge, which may be due to the appearance in this region of pressures of a transient state between the first phase (directed stream of electrons) and the second phase (plasmic). In the transient state magnetic focusing of the electronic beam takes palce. The occurrence of focusing of the beam is substantiated by the calculations of the authors as well as by their own experiments.

Investigation of the time dependence of the development processes of the vacuum breakdown was made by different methods: recording oscillographically the potentials and currents during breakdown, measuring the time of X-ray production, and recording light phenomena during breakdown with the help of a rotating mirror. Some idea can be obtained about the time involved in the breakdown development, if the pulse coefficient for the vacuum gap, that is, the ratio of breakdown potential for pulses of given duration to that for a constant potential, is known.

Experimental data show that the time characteristics of the breakdown are different under different conditions.

According to data from Spivak and Dubinina (ref. 13), with small distances between electrodes (0.01 mm) and small potentials, the change from d-c potentials to pulses (square pulses of duration 1 - 10 μsec) greatly increases the breakdown potential. If, in the static case, the breakdown took place at 300 volts, then pulsed potentials of more than 2 kv were possible. Such a large pulse coefficient shows that, for the conditions used, the time of breakdown development is on the order of a few microseconds. Under approximately the same conditions, Boyle, Kisliuk, and Germer (ref. 54) measured breakdown development times on the order of microseconds. Significant pulse coefficients were also noticed by Mason (ref. 2) for pulse durations of microseconds for small electrode spacings and potentials up to 60 kv.

Pulse coefficients on the order of 1.5 - 2 and larger are also observed in the case of breakdown along the insulation in vacuum with pulses of microsecond duration and potentials of tens of kv. This effect is used in pulse oscillography (ref. 14).

Pulse coefficients different from unity were also discovered for large breakdown potentials. In the work of Halpern (ref. 15), a vacuum gap of 5 cm withstood pulses of high-frequency voltage of 2,000 kv. The potential was supplied at a frequency of 3,000 mc, and a pulse duration of 2 μsec. With a d-c potential on the same gap, the breakdown takes place at potentials less than 800 kv.

Dyke and Trolan (ref. 7) made oscillographic recording of the currents and potentials during breakdown in the case of a sharp cathode and a flat anode, with potentials of several thousand volts. Under such conditions, the time necessary for the development of breakdown is about 1 microsecond.

A time for the development of breakdown of about 2×10^{7} sec was obtained by Warmoltz (ref. 16; 15 kv, tungsten spheres at a distance of 0.25 mm) and by Schäffer (ref. 17; 28 kv, breakdown between the plates of the oscillograph at a distance of 15 mm).

Hull and Burger (ref. 18) established that, with distances between the tungsten electrodes of about 2 mm and the potential up to 100 kv, the transition to an arc in metal vapor takes place in less than 10^{-7} sec.

The instantaneous appearance of light phenomena which accompany the breakdown was studied by Snoddy (ref. 19) and Chiles (ref. 20) with the help of the camera and the rotating mirror. It was established

that, with the exception of rare cases, glow first appears at the anode and appears at the cathode afterwards in some time interval (1 to 2 $\times 10^{-7}$ sec according to Snoddy, or, 1.3 to 9.3 $\times 10^{-8}$ sec according to Chiles). Chiles also measured the spreading speed of the glowing clouds of metallic vapor for different anode materials. These speeds lie in the region 5.0 to 8.9 $\times 10^{5}$ cm/sec.

2. Electrical Breakdown in High Vacuum With Small Distances Between Electrodes and Relatively Small Potentials

For the case of nearly uniform fields, small distances between electrodes (up to 0.01 mm) and small potentials (up to 20 - 50 kv), the mechanism of vacuum breakdown is considered known. Experimental data (refs. 2, 1, 6, and 54) show that in this case the field intensity on the surface of the cathode, before breakdown, is sufficient to cause field emission from the rough cathode surface. The electrons of the field emission current are accelerated between the electrodes to high speeds, and they bombard the anode. The surface of the anode is heated locally to very high temperatures, causing appreciable amounts of gas and metal vapor to be liberated. The high vacuum is destroyed, and gaseous breakdown takes place in the usual way. Thus, for the case of small electrode gaps and small potentials, breakdown occurs when the field intensity E at the cathode is greater than a critical field E_{cr}, causing a noticeable field emission current:

$$E \geqq E_{cr} \tag{2}$$

More exact criteria for electrical breakdown with small gaps and small potentials have been developed by Boyle, Kisliuk, and Germer (ref. 54). The experiments were conducted with pressures on the order of 10^{-9} mm Hg, with two crossed tungsten wires of 0.75 mm diameter, and a gap between them of less than 8×10^{-4} cm. The breakdown potential was less than 2.2 kv. The experiments confirmed the breakdown mechanism described above. With the potential less than the breakdown potential, field emmission currents from 10^{-8} to 10^{-2} amp were observed and measured in constant and pulsating fields. The breakdown potential - electrode spacing curve was approximately linear; that is, the critical field intensity was essentially constant for different gaps.

Based on experimental data, it is calculated that the power produced on the anode due to its bombardment by the field emission electrons, even with allowance for loss of heat due to conduction, is sufficient to cause evaporation of the metal anode surface. The metallic vapor is partially ionized by the electrical current from the cathode, but,

according to calculations by the authors, the ion current is several times smaller than the electron current.

Approximate calculations made by the authors, using simplified formulas, allow us to determine the field emission current density j_E under the influence of a field $E = E_A + E^+$, where E_A is the applied field, and E^+ is the field produced by the presence of positive ions. For j_E the following relation can be developed:

$$j_E = j_0 e^{Mj_E^2}$$

where j_0 is the current density without consideration of the influence of the positive ions, and M is Constant. A graphical solution of this equation and the investigation of stability leads to the condition for breakdown:

$$\frac{j_E}{j_0} = \sqrt{e} \approx 1.65 \qquad (3)$$

The electrical breakdown between the electrodes comes when the space charge due to positive ions is sufficient to increase the field emission current by 65 percent over the current which could exist without the space charge.

After an increase in the field to a value sufficient to cause breakdown, there is still no noticeable increase in current for a period of approximately 1 microsecond. This time is necessary for the heating and evaporation of the anode material. An estimate of this time by the authors agrees with the experimental data. Following the evaporation of the anode material, a rapid increase in current takes place in less than 10^{-8} sec.

As the distance between electrodes is increased, the mechanism of breakdown described above slowly changes to the mechanism of breakdown for high potentials and large interelectrode distances (ref. 21). Mason (ref. 2), and Hull and Burger (ref. 13) observed the breakdown potential to be connected with the field emission and anode evaporation processes for several large distances and potentials.

In Chiles' work (ref. 20), a mixed mechanism of breakdown was observed for potentials of 55 - 120 kv, dimensions of electrodes on the order of 1 mm and approximately the same gap. According to his view, the field emission currents heat the anode and a cloud of vapor is

produced which moves toward the cathode. The positive ions move much faster than the rest of the cloud. The bombardment of the cathode by the positive ions and the increase in field intensity at the cathode, because of the approach of the positive ions, bring about additional electron emission. The occurrence of positive ion bombardment of the cathode is accompanied by a glowing of the cathode surface. The glow of the electrodes and the movement of a cloud of vapor from anode to cathode were observed by Chiles with the help of a rotating mirror camera.

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Mason's experimental data (ref. 2) for electrode gaps from 0.2 to 0.7 mm show that the pulse coefficients in this case can be explained by the above mechanism if the speed of the vapor cloud from the anode is about 10^5 cm/sec. Similar speeds were found experimentally for a mercury anode in a hydrogen atmosphere (ref. 22). The speed of the cloud was found to be independent of the pressure. Very similar speeds were also obtained in the works of Chiles.

3. Electrical Breakdown in High Vacuum With Large Distances Between Electrodes and Large Potentials

As can be seen from the curves of figure 1, the breakdown potential increases much more slowly with an increase in gap than condition (2) demands, and the breakdown field strength at the cathode decreases steadily (ref. 6). For example, with a breakdown potential of 650 kv the gradient on the cathode is less than 100 kv/cm. With this gradient the field emission currents, which insure a breakdown, cannot appear. Apparently, the breakdown potential for large gaps is determined not only by the field intensity but also by the total potential.

Different ideas were considered about the possible causes of the high-potential vacuum breakdown. The most promising two hypotheses are:

(1) The exchange of charged particles and photons, and

(2) the release of large pieces of matter from the surface of the electrode.

Let us examine each of these mechanisms in detail.

(a) The mechanism of mutual exchange of electrons, ions, and photons between the cathode and anode.- For an explanation of the processes taking place during the breakdown with large gaps, Trump and Van de Graaff (ref. 6) studied the breakdown, with consideration of the influence of the total potential between the electrodes on the electrical strength of

the gap. The work of Trump and Van de Graaff indicates that the breakdown can develop from the accidental introduction of one or more electrons into the gap. Electrons moving from the cathode are accelerated to great velocities by the electric field. In the collision with the anode, the electron gives off positive ions and X-rays. These ions and photons, impinging on the cathode, cause further electron emission. When the conditions in the discharging gap become such that the mutual interchange is self-sustaining, breakdown takes place.

For the quantitative formulation of the condition for breakdown we introduce the following symbols:

A — the average number of ions released from the anode by the collision of one electron

B — the average number of secondary electrons released from the cathode by one of these ions

C — the average number of X-ray quanta radiated by the anode during the impact of one electron

D — the average number of secondary electrons produced by the cathode under the influence of one of the X-ray quanta

Then the condition for breakdown can be written in the following form:

$$AB + CD \geqq 1 \qquad (4)$$

It is expected that the coefficients A, B, C, and D should increase with an increase in the accelerating potential between the electrodes. Also, they depend on the gradients at the surfaces of the electrodes and on the electrode material and the condition of their surfaces. However, the available experimental data show that the left side of the relation (4) is always less than one.

The value of coefficient A determined by Trump and Van de Graaff in their early work was 2×10^{-4} - 2×10^{-3} for potentials up to 230 kv. The measurement was later subjected to a serious criticism by Filosofo and Rostagni (ref. 23). In their tests the number of ions released per incident electron with a potential of 70 kv come out to be about 200 - 2,000 times less than in the experiments of Trump and Van de Graaff[1].

[1]Filosofo and Rostagni believe that the higher values of coefficient A obtained by Trump and Van de Graaff are connected with the presence of adsorbed oil vapor on the surface of the anode. In the tests of Filosofo and Rostagni the oil vapors were condensed out.

The effective values of coefficient A can be increased somewhat, at the expense of the secondary electron emission. According to the measurements of Trump and Van de Graaff (refs. 6 and 24) the value of secondary emission in the range of potentials 30 - 340 kv does not exceed 8 (tungsten anode).

The value of the coefficient B (number of electrons per incident positive ion) was measured by many authors (refs. 6, 25, 26, 27, 28, 29, 30, 31, and 32) under different conditions and for different ions. According to their data the coefficient B does not exceed 25. Therefore even if we take the maximum value of A as given by Trump and Van de Graaff, and take the maximum possible value for B, the value of the term AB in relation (4) will be less than 0.4.

Recently, Bourne (ref. 33) has published some interesting observations of the exchange mechanism. The energy produced on the electrodes by the charge carriers of the pre-breakdown current for potentials of about 100 kv was measured by measuring the temperature of the corresponding electrode. The comparison of data obtained by this method showed that the positive ion current comprises from 0.1 to 0.9 percent of the total current. Bourne believes that the magnitude of the pre-breakdown current is basically determined by the electron currents due to field emission. Because of the small value of coefficient B, the observable pre-breakdown currents cannot be explained by exchange processes.

The second term of relation (4), the product CD, is small, even according to the authors of the hypothesis. Special experimental measurements of C and D were not made. Tentative calculations show that, at least for potentials to 1,000 kv, the term CD does not exceed 0.09. Fünfer established experimentally that the irradiation of the vacuum gap by intense X-rays has no influence on the electrical strength (ref. 21).

Also, the mechanism of electron-ion exchange does not agree with data for the vacuum electrical strength under short pulsed potentials. With a frequency of 3,000 mc and potentials of 2,000 kv (ref. 15), even the lightest ion will not have time to cross the interelectrode distance of 5 cm in a time of one half-cycle.

These calculations and data show that in its original form the mechanism of exchange of charged particles and photons is not confirmed by the experiments. Recently, efforts have been made to include in this hypothesis the idea of the presence of negative ions in the exchange process (refs. 28, 31, and 32). It is supposed that the positive ions, in the impact at the cathode, knock out negative ions as well as electrons. The coefficient of the secondary emission

of the positive ions under the action of a bombardment of negative ions is undoubtedly much larger than under the bombardment of electrons. In this case the probability of the occurrence of the exchange mechanism is greater.

A significant influence of the negative ions on the breakdown process was established in tests by MacKibben and Boyer (ref. 9). A magnetic field applied to the interelectrode space was of such a strength as to deflect electrons, but not appreciably change the path of the negative ions. The electrons missed the anode, as shown by the absence of X-rays. Nevertheless the breakdown potential of the gap did not change. This indicates a definite participation by the negative ions in the breakdown process.

(b) Mechanism of the release of particles from the electrodes.- In 1952 Granberg (ref. 3) introduced the following hypothesis to explain the mechanism of high vacuum breakdown. He believes that breakdown takes place due to the ejection of comparatively large particles of matter from the electrodes. These particles are considered electrically connected to the electrodes, and their separation is caused by the coulomb repulsion in the highly charged electrode. The charged particles are accelerated to large energies in the interelectrode field and create very high local temperatures upon impact with the opposite electrode. It is assumed that these high temperatures lead to the development of the breakdown.

For the quantitative formulation of the hypothesis, Granberg introduces the following symbols:

W — the energy per unit area, incident on the electrode under the impact of the particles

C' — some energy constant, characteristic of the electrodes

Then the conditions for breakdown are written

$$W \geqq C'$$

But $W = \sigma U$, where σ is the charge per unit area on the surface of the particle and U is the potential between electrodes. If E is the field strength on the surface of the electrodes before the particles break away, then, as an approximation, it can be considered that $\sigma \approx E$. Then the breakdown criteria can be written:

$$UE \geqq C \qquad (C \text{ is Constant}) \qquad (5)$$

In the case of a uniform field, $E = \frac{U}{d}$, then the final breakdown criteria has the form:

$$U \geqq (Cd)^{1/2} \qquad (6)$$

that is, the breakdown potential is proportional to the square root of the distance between electrodes, for a given pair of electrodes in a uniform field. Granberg studied the data found in the literature on the dependence of breakdown potential on gap distance, to correlate the experiments with relation (6). These data are given in logarithmic form in figure 2. All experimental points (with the exception of three points by Gleichauf) fall on the straight line with slopes approximately 1/2. Thus, existing experimental data agree with the formula over the wide range of voltages of 20 - 7,000 kv, and a range of gaps from 0.1 mm to 6 meters. The value of constant C is a function of the condition of the electrodes and is usually about 10^{11} v^2/cm.

With nonuniform fields, relation (6) is no longer correct, but relation (5) still holds; that is, the breakdown is a function of the applied potential and the field strength at the electrodes. From table II it can be seen that the values of C for nonuniform fields are similar to those for uniform fields. To Granberg, this indicates that the concept of the ejection of particles from the electrodes is a valid one for nonuniform fields.

On the basis of this mechanism, it is easy to explain the increase of breakdown potential with multiple discharges, the transfer of material from anode to cathode, and the difficulty of reproducing conditions in the discharging gap (scattering of the values of the breakdown potential).

The breakdown potential is also proportional to $d^{1/2}$ for the case of breakdown along the surface of a cylindrical dielectric between flat electrodes, but in this case the value of C is smaller, about 3×10^9 v^2/cm.

Granberg has tried to determine the local temperatures which are generated in the target electrode by the impact of the particles, and also the speeds of these particles before impact, using approximate calculations. The energy produced by the impact is expressed as follows:

$$W' \approx QU$$

where Q is the charge of the particle. Using the relations

$$Q = \sigma\pi r^2 \qquad (r = \text{radius of particle})$$

$$E = 4\pi\sigma$$

$$E = U/d$$

$$U = Cd^{1/2}$$

we get

$$W' \approx \frac{Cr^2}{4}$$

This energy is associated with a section of electrode target of area πr^2 and a depth of n atomic layers. The number of atoms contained in this volume is $\frac{\pi r^2 n}{a^2}$, where a is the distance between atoms. Now we can write:

$$W' \approx \frac{3}{2} kT \frac{\pi r^2 n}{a^2} \approx \frac{Cr^2}{4}$$

where k is the Boltzmann constant and T is the absolute temperature. From this we can find the local temperature T, produced by the impact. The number of layers n is still unknown.

$$T \approx \frac{1}{6\pi} \frac{Ca^2}{kn} \qquad (7)$$

Substituting representative values for C, a, and k, we get, for $n = 1$, $T \approx 10^6$ °K. It follows that, even for n equal to several hundred atomic layers, we can expect a temperature which exceeds the melting point of the metal.

If the particles are considered spherical with a radius r and a density of about one, then their speed at the end of their flight can be found from the relation $\frac{mv^2}{2} = W'$, where m is the mass of the particle

$$v \approx \sqrt{\frac{1}{8} \frac{C}{r}} \qquad (8)$$

For particles with radii of 10^{-2} to 10^{-6} cm, the velocities lie in the region 10^4 - 10^6 cm/sec. For agreement with Granberg's theory, the time for the development of breakdown for a 1-cm gap must not be less than 1 microsecond. This is not true with the majority of experimental data.

Granberg's mechanism cannot explain the presence of bursts of X-rays during breakdown. Also, it is not clear which particles Granberg has in mind. If they are surface impurities, then this is not a general case; with proper treatment of the electrodes, they can be eliminated. If they are particles of the electrode metal, then the mechanism of their interaction with the electrode and their ejection is not understood.

Granberg's most useful contribution is the tabulation of a large number of experimental results (fig. 2 and table II). Besides that, it can be considered proven that if, with a sufficiently long application of potential, a particle can tear itself away from the surface of one of the electrodes, then breakdown will result. However, the explanation of breakdown in the general case by this means is not possible.

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4. The Electrical Discharge in a Very Nonuniform Field

In the case of very nonuniform fields, the high-vacuum discharge occurs, with comparatively small potentials, even with substantial electrode gaps. In this case, the potential gradients in one or both electrodes (point-plane, point-point, thin wire-cylinder, etc.) are large. In early experiments, the magnitudes of these gradients were not calculated, as the exact geometry was not known. To determine the mechanism of breakdown with such experiments is difficult.

Figure 3 gives the relationship between breakdown potential and electrode gap for the point-plane configuration, obtained in 1947 by Hashimoto (ref. 41). The radius of the point is not known. The three lower curves were obtained with the needle negative - the three upper ones with the needle positive. It can be seen that with the negative needle the breakdown occurs at considerably lower potentials. The relation between breakdown potential and gap distance is approximately linear. In the same paper there are some interesting photographs of the surface of the flat electrode after breakdown, but they are not explained in any way.

It is believed (ref. 42) that the high-vacuum discharge in the case of the point-plane (point positive) or the wire-cylinder (wire positive) is caused by the release of positive ions from the anode under the influence of the strong field. The breakdown potential increases with heating of the anode, annealing of the whole tube, or allowing a few discharges. However, according to Leb (ref. 43) this mechanism is not likely, since the emission of ions under the action of strong fields has never been observed.

The high-vacuum discharge for the case of a negative point and a plate was studied in detail by Dyke and Trolan. For their tests, a

tungsten needle served as the cathode. The anode was a molybdenum plate 5 mm from the cathode. The structure of the electrodes was studied before and after breakdown with an electron microscope. The electrodes were in a soldered sphere with a powdered desiccant. The pressure of chemically active gases was approximately 10^{-12} mm Hg. Under such pressures, the surfaces of carefully degassed electrodes can be considered free from adsorbed gases. The experiments were conducted with pulsed potentials of 2 to 35 kv, with durations of 2 to 1/2 μsec. The shape of the pulses was nearly square.

Curves giving the dependence of the current density on the potential applied were obtained for several tungsten cathodes. With current densities on the cathode from 6 to 6×10^6 amp/cm^2, the experimental data coincide with the theory of field emission (eq. 1). For current densities from 6×10^6 to 1×10^7 amp/cm^2, the calculated values are greater than the experimental ones. This is explained by the presence of a space charge of electrons near the point. With a current density larger than 1×10^7 amp/cm^2, breakdown occurred. The radius of the point, before breakdown, was a fraction of a micron, and the results of the experiment were repeatable. After breakdown, the point was melted and its radius increased by tenths of microns.

L 1203

The process of transition from field emission currents to the vacuum arc was investigated oscillographically. With comparatively small voltage pulses, the current waveform has a constant level, about 1 μsec in duration. This is the field emission current. An increase in potential results in an increase in the current during the pulse. If the potential is increased by approximately 1 percent, the current grows slowly during the first microsecond (as in the preceding case), then increases suddenly by about a factor of 2 (breakdown). The step transition lasts less than 5×10^{-8} sec. The field strength necessary for the breakdown is about 8×10^7 v/cm.

The authors imagine the mechanism of breakdown as follows. The field emission currents, on reaching large densities, heat up the thin point of the cathode. The heating occurs because of the small cross section of the point and its high resistance. The heat causes thermionic emission, leading to the slow increase in current during the pulse. As the current increases, the temperature of the point goes up until the evaporation point is reached. At this point gaseous breakdown takes place in the metallic vapors.

Dyke, Trolan, and others (ref. 44), by using a simple electro-optical arrangement, were able to get pictures showing the portions of the cathode which were radiating electrons. This work was done with

pulses of 1 μsec duration. An analysis of the photographs shows that, for the period of current growth during a pulse, the current is more evenly distributed over the surface of the cathode, a large emitting area. These effects confirm the influence of the space charge on the emission. The current density immediately before breakdown is larger than the current density predicted by the field emission theory. Evidently, the thermionic emission contributes significantly to the current. The theoretical temperature, calculated by considering the heat conductivity of the metal, gives values for the thermionic emission which account for the difference in observed and theoretical currents. The authors have shown that, for a sharp cathode and a flat anode, the bombardment of the negative point by positive ions is not essential for breakdown. The breakdown can occur in less time than is required for an ion to traverse the interelectrode distance (for instance, breakdown in 1/2 μsec, with a potential less than 10 kv and a gap of 8.5 cm).

Another argument against the assumption that ions and particles from the anode take part in the breakdown is the fact that the breakdown condition depends only on the field strength at the cathode, and not on the applied potential. This is true in the region 5 - 60 kv. However, with a poorly degassed anode the positive ions can take an active part in the breakdown. Electrons emitted by field emission from the sharp cathode can, upon impact at the anode, release and ionize the adsorbed gas (ref. 4).

II. THE INFLUENCE OF SOLID DIELECTRIC ON THE HIGH-VACUUM DISCHARGE

The electrodes in a vacuum tube are always separated by an insulator which surrounds the vacuum volume. In practice, in most high-voltage apparatus, the surface of the insulator plays a decisive role in the development of the breakdown process. In vacuum high-voltage devices with glass envelopes (X-ray tubes, for instance), the breakdown is accompanied by an intense glow on the glass surface, indicating a participation of the glass in the breakdown process. The breakdown potential of such an arrangement depends on the type of envelope and its properties (purity, degassing, and electrical conductivity of the surface) and is much smaller than the breakdown potential of the gap itself. Under certain conditions glowing of the glass or glowing spots on the glass can be observed when there is no breakdown (ref. 45). All these effects on the glass envelopes of X-ray tubes are usually explained by the bombardment of the glass by primary and secondary electrons (ref. 8).

The high-voltage routine has a large influence on the electrical strength of the finished product. It generally consists of successive slow increases in potential, below the breakdown potential, alternating with "rest periods" in which the voltage is held constant. Using such a routine, the stability of the tube can be increased by more than 100 percent (ref. 8). However, with improper application of the routine, the electrical properties of the apparatus can be made much worse. This is observed if, during the routine, very large breakdown currents pass through the tube. The intense production of gas, contamination of the electrode surfaces, and deposition of electrode material on the glass often leads to unserviceability of the tube. Therefore it is necessary during the routine, and, if possible, during the operation of the device, to install a limiting resistance in the power supply. It has been found experimentally that the magnitude of the limiting resistance must be on the order of 1 ohm per volt of operating potential, in the range 30 - 200 kv (ref. 8).

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Of the many different forms of insulator, we can consider known only the simplest case: a cylindrical insulator in a uniform field (provided cylinder is oriented along a line of force of the field). The breakdown along the surface of such a cylinder, with constant potentials up to 100 kv, was studied by Gleichauf (refs. 46 and 36). Different insulating materials, in the form of rods (or tubes) with a diameter of 13 mm and a length of 23 mm, were investigated.

The author's findings did not support the dependence of breakdown potential on pressure of the residual gas, in the interval of 5×10^{-3} to 10^{-7} mm Hg. Neither did they support the dependence of the breakdown potential on the material of the electrode (stainless steel, brass, magnesium, aluminum) for insulators made of pyrex glass and fused quartz.

In figure 4 is shown the dependence of the breakdown potential on the length of the insulator, for the case of hollow pyrex cylinders 51 mm in diameter with a wall thickness of 1.9 mm. The breakdown potential does not increase linearly as in the case of the vacuum gap, but the absolute values of the potentials are actually lower.

Table III gives the dependence of the breakdown potential on the material of the insulator. Analyzing these experimental data, Gleichauf comes to the conclusion that the breakdown potential does not depend on the vapor pressure of the insulator, its dielectric constant, or its density, but is determined strictly by surface resistivity of the insulator. With a decrease in the surface resistivity, the breakdown potential falls. A roughly finished or frosted surface of the glass or quartz corresponds to an increase in breakdown potential of about 40 percent. In particular, the roughness of the cylindrical surfaces near the cathode

has considerable effect on the breakdown potential. The roughness of the anode end of the insulator has less effect. Gleichauf especially emphasizes the importance of the condition of the cathode and the surrounding area on the breakdown. According to his data, the quality of the contact between the cathode and the insulator has a noticeable influence on the breakdown potential. Also, if the cathode is covered by a thin layer of glass, the breakdown potential is affected.

In order to determine the mechanism of breakdown on the surface of a dielectric, Gleichauf investigated the pre-breakdown stage, that is, the nature and the magnitude of currents flowing in a given construction with potentials lower than required for breakdown. Indirect measurements were made of the pre-breakdown currents by observing the resultant X-rays with a Geiger counter placed outside the vacuum chamber. With such a method, only the electron current in the vacuum space was measured (leakage current does not contribute to the X-rays). In the article the nonlinear relation between the pre-breakdown current (in the interval 10^{-11} - 10^{-8} amp) and the potential (40 - 65 kv) is shown. Although the points were widely scattered, there is a general tendency for the current to increase with an increase in potential. The large scatter of the experimental points is also observed for vacuum gaps without insulators. Use of the high potential routine (without breakdown) noticeably reduces scattering. It would be natural to assume that the breakdown takes place after pre-breakdown currents of a definite critical magnitude flow. However, in practice such a critical magnitude does not exist. The breakdowns took place with pre-breakdown currents varying by several orders of magnitude (5×10^{-11} to 5×10^{-7} amp). Gleichauf believes that the pre-breakdown currents are caused by field emission.

Besides measuring X-ray radiation with a Geiger counter, use was made of a camera obscura and filters. This made it possible to determine the origin of the X-ray emission and its intensity.

It was found that, at the beginning of breakdown, the insulator is negatively charged and repels electrons. Because of this, the area of most intense radiation on the anode is slightly removed from the insulator. Only low-speed electrons hit the anode near the insulator. This occurs when the development of breakdown leads to a significant reduction in the interelectrode potential.

Oscillographic investigations show that, during breakdown, the potential falls from 10 - 15 kv to hundreds of volts (sometimes to 2.5 kv). The low-voltage arc, which ignites as a result of breakdown, cannot burn with a current less than 1 ampere, either with or without the insulator. If the internal resistance in the circuit will not allow such a current, then only the discharge of the static charge on the electrodes occurs.

Gleichauf also describes the effects of the hardening routine - increasing the breakdown potential by consecutive mild breakdowns - for the vacuum gap as well as the gap with a dielectric (glass, fused quartz). With consecutive breakdowns with the dielectric, the values of the breakdown potential, although they have considerable scattering, generally increase. Evidently the hardening routine influences the condition of the surface of the dielectric as well as the electrodes. If, after such a routine, the potential is not applied for some time, the breakdown potential will decrease, but not as low as it was originally. A similar decrease is observed after a specimen is seasoned at atmospheric pressure. In this case the length of seasoning is not important.

From the experimental data on routines for vacuum gaps, gaps with dielectrics and high-voltage vacuum instruments with glass envelopes, it can be concluded that during the routines both irreversible and reversible processes take place. First, the irreversible processes should include the process of melting of sharp surface irregularities on the electrodes, burning out of foreign particles (dust, for example), and deposition of impurities on the electrodes and the dielectric. It is also possible to improve the degree of vacuum in the tube. During breakdown, gases or ions are liberated from the electrodes and the parts of the dielectric which take part in the breakdown. All of this is actively adsorbed by more distant parts of the tube. As a result, the more important parts of the tube are further degassed. This last process can be considered partially reversible. Finally, the surface charge on the dielectric and high-voltage polarization could (for some geometries) increase the electrical strength by causing a more uniform distribution of the fields. Such effects are undoubtedly reversible.

It is possible that the processes that occur during hardening are not exhausted by the ones mentioned above. It is impossible to imagine clearly the hardening mechanism in all details; so far, many processes during breakdown and the participation of dielectrics in these processes are not explained. Neither Gleichauf nor other authors who observed the behavior of dielectrics during breakdown have described the processes taking place.

No matter what the form of the dielectric (rods between electrodes, outer envelope, etc.) its influence distorts (redistributes) the electric field between the electrodes, both in gas (ref. 47) and in vacuum. The data obtained by Gleichauf with the camera obscura show the redistribution of these fields. Such a change must undoubtedly affect the breakdown potential. The following reasons can be given for the redistribution of the fields:

(1) The dielectric constant of the insulator is always larger than the dielectric constant of free space, therefore by the introduction of

the insulator, the field intensity in the vacuum interlayer between the electrode and the dielectric will be increased. This effect of redistributed capacity plays a decisive role in the case of alternating current or pulsed voltages when the leakage on the insulator and the formation of surface charges do not have time to occur.

(2) The surface resistance of an insulator can be different in different places; then from the leakage currents, different potential drops will appear at different sections.

(3) Distortion of the field can come about because of surface changes on the insulator resulting from pre-breakdown radiation or from preceding discharges.

(4) When the dielectric includes a cavity with a lower dielectric constant (for example, a loose fit of dielectric to electrode) then the potential across this cavity is high and a local breakdown can take place. The spark in such a breakdown serves to excite the whole mating surface of the insulator. Such ignitions in the joints of the electrode-insulator structure are often observed (ref. 45).

(5) The fields near the electrodes can be changed by the action of high-voltage polarization of the dielectric or the collection of space charge in the region of the electrode (ref. 48). The time required for the high-voltage polarization effect is measured in minutes; therefore for a-c. and pulsed potentials, it does not have to be considered. In figure 5, the potential distribution in quartz is given (ref. 48). The straight line corresponds to the distribution immediately after the application of the voltage. The other curves were taken after some time had elapsed. It can be seen that, in quartz, charged layers are formed in the vicinity of both electrodes, tending to oppose the applied voltage. For some dielectrics the charged layer can only form near one of the electrodes.

The effects can be explained by the transfer of ions of the dielectric under the action of the electric field. For example, during moulding of the glass, the high-speed alkaline ions drift to the cathode, leaving a layer of quartz near the anode (refs. 49 and 50). In this case the electrical conductivity changes in some regions according to changes in composition; this increases the irregularity of the field.

The above polarization (charge opposes the applied potential) is sometimes called "inner polarization." In some cases, "outer polarization" - charge layers leaving the same charge as the adjacent electrodes - can occur. This effect is observed in all dielectrics when the applied field is greater than some limiting value (9 kv/cm for glass).

For "outer polarization" the charges are either generated on the surface of the electrode dielectric spacing or they cross over from the electrode into the dielectric (ref. 51). The decay time for the high-voltage polarization charges, after the potential is removed, is different under different conditions; usually, it is on the order of several hours or days.

As shown by the above discussion, the introduction of a dielectric into the vacuum gap considerably distorts the electric field. This distortion depends on the properties of the dielectric, its form, the shape of the electrodes, and the duration and magnitude of the applied potential. However, the participation of the dielectric in the breakdown is apparently not limited to distortion of the fields. The insulator can also supply the charge carriers necessary for breakdown. This can take place under the action of either a high applied potential (field emission from dielectric) or the bombardment of the insulator by particles (secondary emission, liberation of gas). L 1 2 0 3

In selecting the correct configuration and dimensions of high-voltage vacuum devices, it is necessary to remember that the breakdown potential increases slower than the dimensions of the insulator (see fig. 4). For a device with a fairly high breakdown potential, an increase in size does not lead to a noticeable increase in the electrical strength. For this reason, the manufacture of vacuum tubes for potentials higher than 200 - 300 kv is burdened with great difficulties. For such potentials, sectionalized tubes are usually used, in which a series of intermediate electrodes are situated between the anode and the cathode, and are held at different intermediate potentials (usually up to 100 kv per section). The potentials on the intermediate electrodes are fixed either directly (with a potentiometer, for example) or, with a-c or pulsed potentials, by capacitive action.

In the sectional tubes, the distribution of potential on the envelope is more uniform, and for this reason the resistance to breakdown is considerably higher. The dependence of the potential difference across the insulating part of the section on the length was studied by Neuert (ref. 52).

There is still one original solution of the electrical strength problem: creation of a semiconducting layer on the surface of the dielectric. Blodgett (ref. 53) describes in detail the technology involved in the preparation of such a semiconducting covering. A porcelain cylinder was coated on the inside with a lead-silicon glass. Using a special hydrogen process, the lead atoms were placed in the surface layer, and significant electroconductivity was noted on the surface (resistance of surface layer about 160 ohms on a square centimeter). A thin layer of quartz served to protect the semiconducting layer and to increase the electrical strength. It was formed on the surface of the lead-silicon glass by etching in nitric acid.

With the application of a high voltage to the ends of the cylinder, the potential along it was distributed evenly, and the charges which formed in the discharge volume did not concentrate on the walls but flowed out along the semiconducting layer. For the utilization of such semiconducting layers, a length of 38 mm is sufficient for a static potential of 140 kv.

It should be pointed out that, according to the data of Gleichauf, the dielectrics with high surface conductivities have poor insulating qualities in high-voltage experiments. Blodgett, on the other hand, improved the insulating qualities by increasing the surface conductivity. Evidently in Blodgett's case, the mechanism of conductivity is such that high-voltage polarization does not appear, and the potential is distributed evenly and effectively along the coated cylinder. In Gleichauf's case, the larger surface conductivity was associated with a larger high-voltage polarization, and consequent larger distortion from a uniform field.

Blodgett's result, namely a breakdown value of the field along the surface of the insulator of 3.5 kv/mm, is one of the larger ones published. In present high-voltage tubes, working in the potential range of 100 - 200 kv, the field strength along the surface of the glass does not generally exceed 1 kv/mm.

CONCLUSION

The experimental data and hypotheses show that at the present time there is no clear picture of all the phenomena taking place during a high-vacuum breakdown. However, for certain specific conditions, we can consider the basic processes taking place during the vacuum breakdown to be explained. Such a case is the weak vacuum (on the order of 0.01 mm Hg) in the region of relatively low voltages (up to 20 - 50 kv), when the breakdown develops as a result of the heating up of the anode surface by field emission current.

Also satisfactorily explained is the mechanism of breakdown in a very inhomogeneous field, as in the case of a sharp, pointed cathode and a flat anode at very high vacuum. The experimentally observed properties under these conditions are in good agreement with the hypothesis of heating and vaporization of the cathode point under the action of the field emission current.

In the more general and more important cases of large distances and large potentials, a satisfactory theory does not exist. Under certain conditions the emission of particles from the surface can take

place. However, this hypothesis does not explain many phenomena which take place during high-vacuum breakdowns (X-ray burst, time of development of breakdown). The mechanism of exchange of charged particles between the electrodes can be applied more universally when we take into account the presence and exchange of negative ions. Not one of the known mechanisms is able to explain the breakdown of the vacuum gap on the application of a short-voltage pulse.

A dielectric in the vacuum gap alters the electric field between the electrodes and takes part in supplying the electrons and ions necessary for the breakdown. Still, the mechanism of influence of a dielectric on the high-vacuum breakdown cannot be considered completely clear. Coating the dielectric with a semiconductive layer definitely increases the electrical strength of high-vacuum instruments. Further study in this direction, evidently, will allow us to reduce the dimensions of similar instruments and still preserve their electrical strength.

In conclusion, the author expresses deep thanks to Doctor of Technical Sciences, V. A. Zukerman, for a detailed consideration of questions touched on in the present work and for valuable suggestions.

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TABLE I.- BREAKDOWN POTENTIAL IN HIGH VACUUM FOR ELECTRODES MADE OF DIFFERENT MATERIALS

Material	Breakdown potential (kv)
Steel	122
Stainless steel	120
Nickel	96
Aluminum	41
Copper	37

TABLE II

Geometry of the electrodes	Anode	Cathode	U kilovolts	$E_{cathode}$ 10^6 v/cm	$UE_{cathode}$ 10^{11} v^2/cm
Cylindrical (ref. 39)	Nickel	Tungsten 0.0125 mm	11 ± 10%	2.6	0.28
		Tungsten 0.04 mm	23 ± 10%	2.0	0.43
Cylindrical (ref. 40)	Nickel (diam. 20 mm)	Thorium coated tungsten 0.015 mm	17	2.0	0.33
		Thorium coated tungsten 0.025 mm	24	2.6	0.62
		Pure tungsten 0.015 mm	15	2.8	0.43
		Pure tungsten 0.025 mm	23	2.7	0.62
Wire parallel to plane (ref. 2)	Brass disk (diam. 50 mm)	Tungsten wire 0.7-mm diameter bent into semi-circle of diameter 25 mm	35	0.6	0.20
Point 1-mm distance from plate (ref. 41)	Nickel plate	Nickel point	30	---	----
	Nickel point	Nickel plate	90	---	----

TABLE III

Material	Rod dimensions		Breakdown potential kv ± 10%
	Length, mm	Diameter, mm	
Fused quartz	22.5	12.0	65
Pyrex glass	22.5	12.5	45
Pyrex glass coated with dry silicon oil	22.5	12.5	56 - 73
Soda glass	22.5	12.5	40
Conducting glass	22.0	≈13	6 - 17
Steatite	22.5	13.0	50
Rutile (titanium dioxide)	22.5	15 0	40
Barium titanate	15.0	15 5	8
Zirconium dioxide	22.5	11 1	40
Polystyrene	22.5	12 5	75
Teflon	22.5	14 0	50
Sulfur	23.0	≈45	45

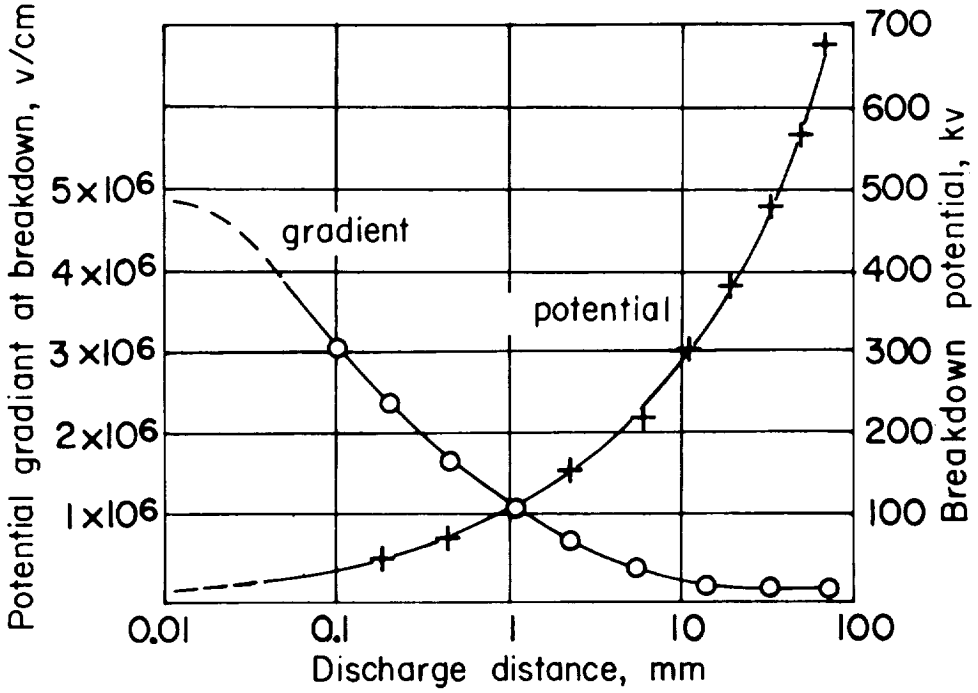
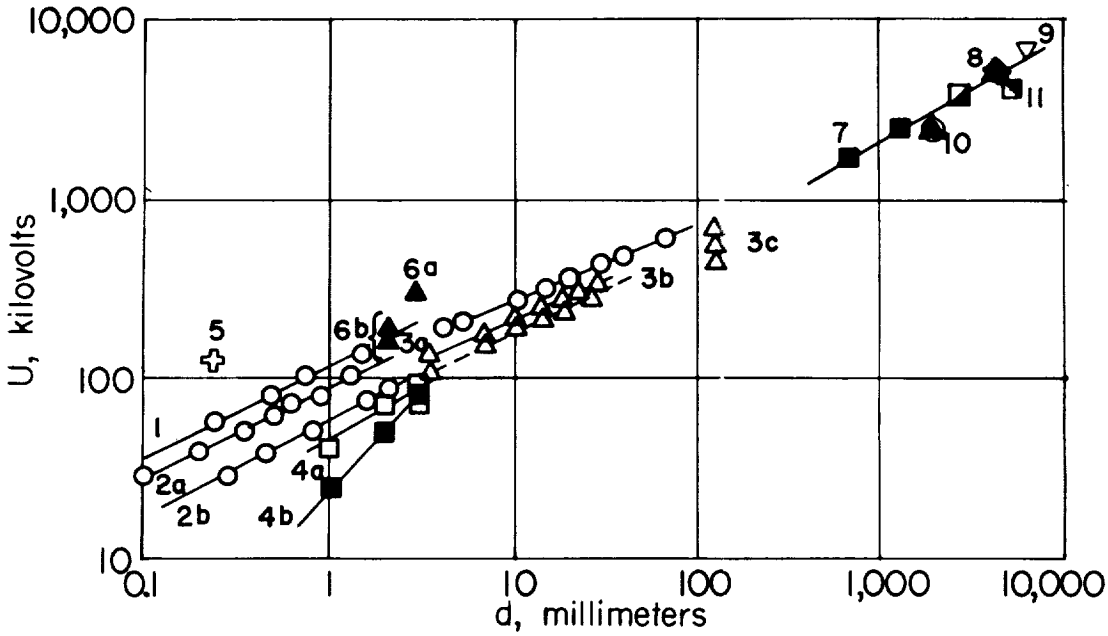


Figure 1.- Breakdown potential (crosses) and field intensity (circles) during high-vacuum breakdown between steel sphere of diameter 25.4 mm (anode) and flat steel disk of diameter 50.8 mm (ref. 6).



1 Spherical steel anode (25.4-mm diam.) and steel disk (50.8-mm diam.); reference 6.

2 Pulsed potential with rise time of 3×10^{-7} sec

2(a) Tungsten hemispheres (50-mm diam.).

2(b) Copper hemispheres (50-mm diam.); reference 34.

3(a) Aluminum sheets.

3(b) Steel sheets.

3(c) Aluminum ring opposite steel anode surface (par· of the electric generator); reference 35.

4(a) Flat electrodes with rounded edges of Kovar (ca·hode) and steel.

4(b) Flat copper electrodes with rounded edges and a hole in the center of the anode (ref. 36).

5 Molybdenum spheres (ref. 37).

6(a) Degassed molybdenum spheres 1 cm in diameter.

6(b) Nondegassed molybdenum spheres 1 cm in diameter (ref. 38).

7 Aluminum electrodes.

8 Robinson's data (unpublished).

9 Aluminum electrodes.

10 Steel electrodes.

11 Steel electrodes.

Figure 2.- The dependence of breakdown potential in vacuum on the electrode spacing for nearly uniform fields, according to Granberg.

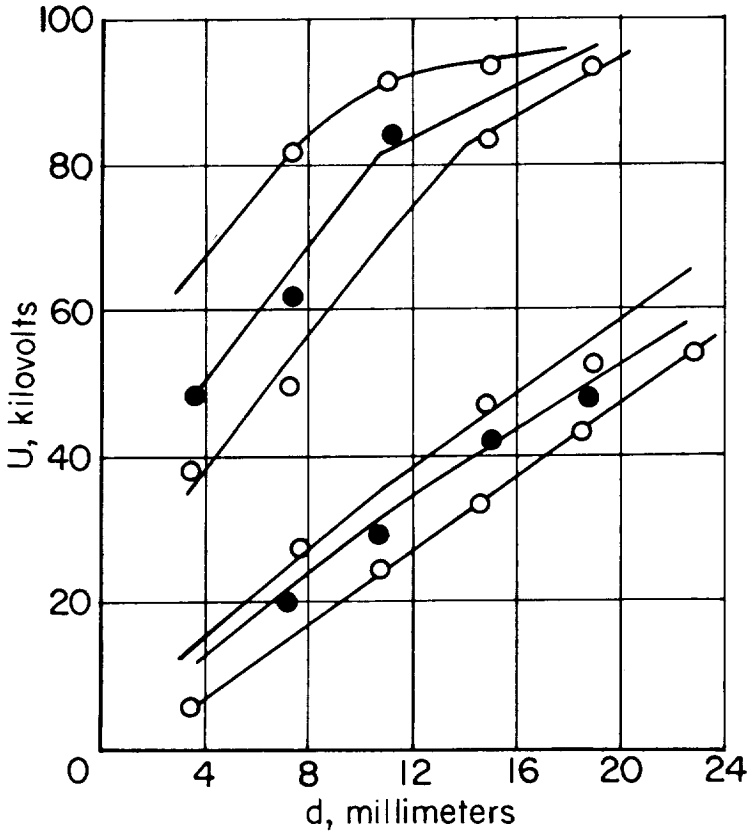


Figure 3.- The breakdown potential for the point-plane electrode configuration in vacuum. The three upper curves correspond to positive needle-negative plane; the three lower, vice versa (ref. 41).

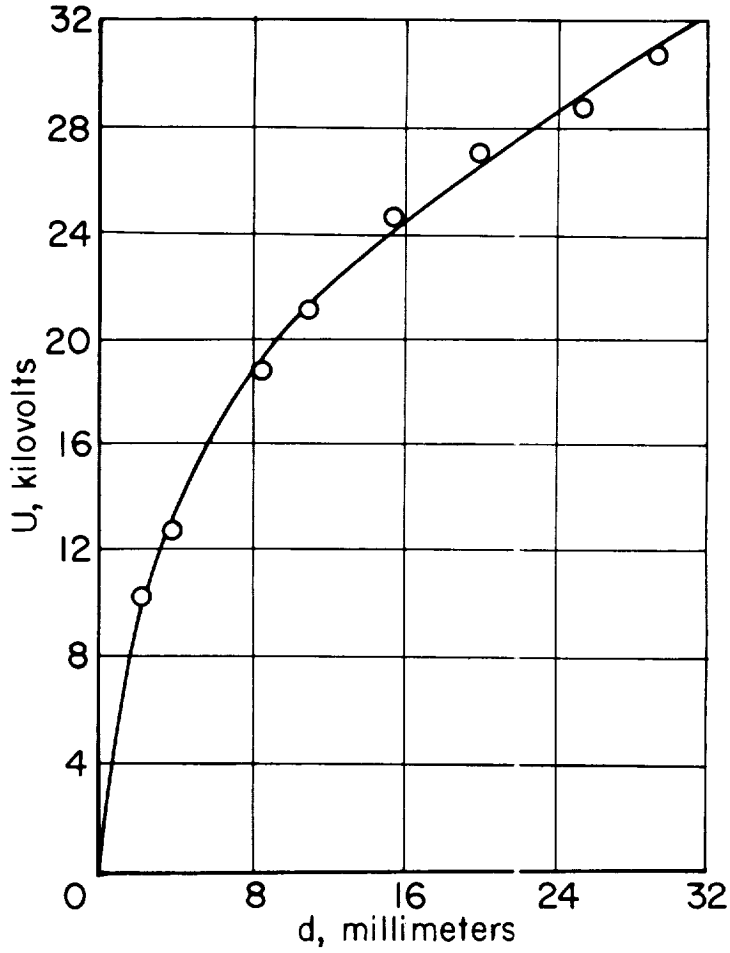


Figure 4.- The breakdown potential versus length of the insulator. Hollow pyrex cylinders of 51-mm diameter with a wall thickness of 1.9 mm (ref. 36).

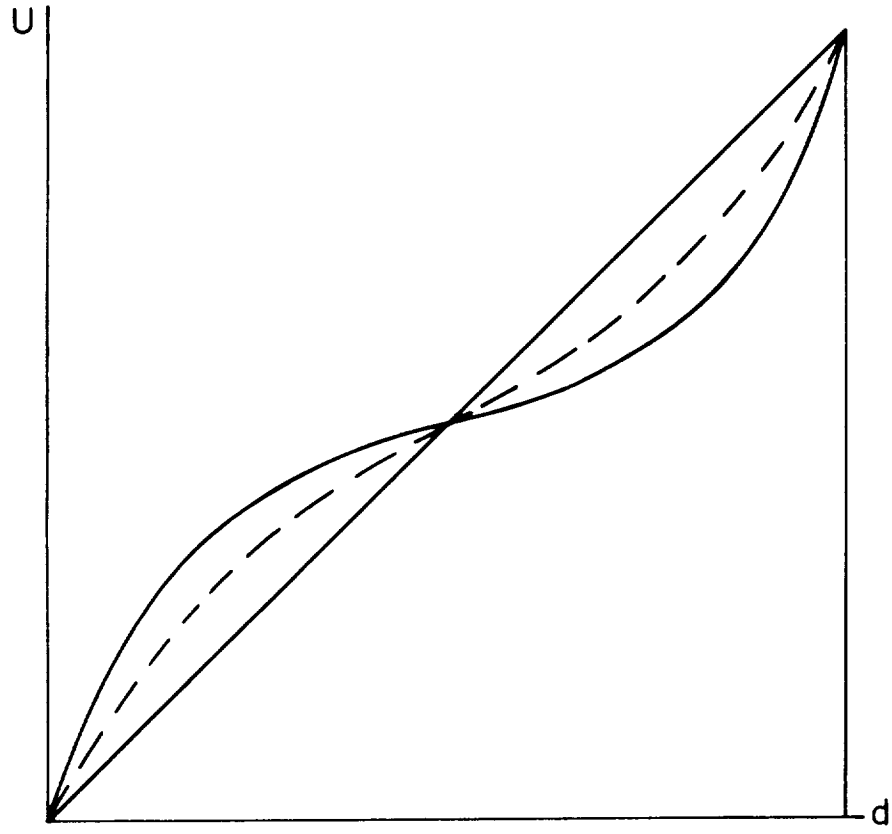


Figure 5.- Potential distribution in quartz.

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